EFFECT OF EXCESS AXLE WEIGHTS ON PAVEMENT LIFE

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Flexible pavement is usually designed based on certain axle load limits and climatic conditions. The Egyptian code has specified certain load limits per each axle type that should not be exceeded. However, many trucks violate these limits by carrying additional weights to decrease the transportation cost. These overweight trucks cause severe deterioration to the pavement and thus reduce its life. The Egyptian authorities generally charges the violating trucks a penalty based on their weights. This penalty could be very small compared to the damage occurring to the pavement based on these over weights. Also, some trucks may carry huge weights that the pavement may not support, so unloading such trucks could be the suitable solution rather than paying few amount of money and deteriorating the pavement. The study aims at studying the effect of axle load increase, and the variation in pavement moduli, on the overall pavement life. It also aims at estimating the overweight truck limits that could be penalized or unloaded. The research uses the KENLAYER software and the Egyptian environmental and pavement materials conditions to estimate the tensile strains occurring under the asphalt concrete (AC) layer and the compressive strains above the subgrade surface. These computed strains are incorporated in the fatigue cracking and rutting models to estimate the pavement life for different axle weights. Results showed that violating trucks should be unloaded when their weights exceed certain limits.

1. INTRODUCTION

Determining the pavement life under given structural, environmental, and traffic conditions is considered the main objective in the pavement design and analysis. The American Association of State Highway and Transportation Officials (AASHTO) Design Guide estimates pavement life in terms of the number of equivalent single axle loads (ESALs). Its design equation was established through empirical analysis primarily based on the AASHO Road Test in Ottawa, Illinois conducted during the late 1950s. More recently, the National Cooperative Highway Research Program (NCHRP) sponsored a comprehensive research study that developed the guide for the “Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures”, which is commonly referred to as the M-E Design Guide. This new guide provides a convenient and more accurate way to determine pavement performance as a function of time or number of axle repetitions under different failure criteria.

The M-E design methods for flexible pavements are based on the assumption that the pavement life is inversely proportional to the magnitude of the traffic-induced pavement strains. One of the most critical locations for hot-mix asphalt (HMA) or flexible pavements is the bottom of the asphalt pavement layer. It has been well established that the measured radial tangential strains (tensile strain) at the bottom of the asphalt layer is directly related to the fatigue life of asphalt pavement[1]. Thus, measuring or predicting the tensile strain at the bottom of the asphalt layer is important to predict fatigue life. Knowing the tensile strain at this critical location, along with the resilient or dynamic modulus of the asphalt layer, in some
cases, enables the prediction of the number of load repetitions to pavement failure. Vertical compressive strains on the top of subgrade of asphalt pavement are another important pavement response to predict the potential subgrade rutting in HMA pavements.

Therefore, two competing failure mechanisms were typically assumed related to the pavement overlay design. These two failure mechanisms are the fatigue cracking (20 percent) of the asphalt bound pavement layers and the rutting (0.5 inch) at the top of subgrade soil due to accumulated permanent deformations. Based on his M-E concept Bayomy et al.\(^2,3\) developed his WINFLEX 2000 software for the design of hot mix overlays. Several fatigue and rutting models have been developed to relate the asphalt modulus and/or the measured strains to the number of load repetitions to pavement failure. Most of the fatigue failure models take the following form:

\[
N_f = f_1 \varepsilon_t^{f_2} E_{1}^{f_3}
\]

(1)

While the rutting models usually take the following form:

\[
N_{r2} = f_4 (\varepsilon_v)^{-f_5}
\]

(2)

where,

- \(N_f\) = the allowable number of load repetitions to prevent fatigue cracking from reaching a certain limit defined by the agency (10-20% of the pavement surface area).
- \(N_{r2}\) = the allowable number of load repetitions to prevent rutting from reaching a certain limit defined by the agency (0.5 inch).
- \(\varepsilon_t\) = the tensile strain at the bottom of the asphalt layer.
- \(\varepsilon_v\) = the compressive vertical strain at the surface of subgrade.
- \(E_1\) = the elastic modulus of the asphalt layer; And \(f_1, f_2, f_3, f_4, f_5\) = regression coefficients.

The values of the regression coefficients shown in the previous equations usually vary according to material type, environment, traffic conditions and the failure limits specified by the agency. Their values, in English units, based on different agencies are presented in Tables (1, 2).

Kapoor\(^{11}\) investigations on both single and tandem axles showed that as the axle load increased, the pavement reached failure at a faster rate, requiring a lower number of repetitions to reach failure. It was also observed that as the axle load increased, the fatigue-based Equivalent damage factor (EDF) increased at a much faster rate compared to rutting-based EDF. EDF is the analysis of relative pavement life based on a standard axle load. The standard axle load chosen was 18,000 lbs for single axle loads and 34,000 lbs for tandem axle loads. Prozzi et al.\(^{12}\) used the concept of Equivalent Damage Factor (EDF) to quantify and compare pavement performance as a function of increasing axle loads. He proposed models that can be used to evaluate the load sensitivity of pavements under diverse conditions and obtain quick estimates of pavement life. He found also that the standard axle load for tandem varies according to the failure criterion used. Its value was found to be about 23 kip under rutting criterion, and about 29 kip under cracking criterion.

2. PROBLEM STATEMENT

Flexible pavements, in Egypt, are designed according to the AASHTO design guide. The axle load limits are specified by the Egyptian General Authority of Highway and Bridges (EGAHB). The maximum allowed axle load for single axle dual tire was 10 tons. Due to the construction of the new International Coastal Highway and the expected international trucks using that highway, the EGAHB proposed increasing the axle load limits. Furthermore, many trucks throughout the country violate the specified load limits by carrying additional weights to decrease the transportation cost. Those overweight trucks cause severe deterioration to the pavement.

The Egyptian authorities generally charges the violating trucks a penalty based on their weights. Such penalty could be very small compared to the damage occurring to the pavement based on these over weights. Also, some trucks may carry huge weights that the pavement may not support, so unloading such trucks could be the suitable solution rather than paying few amount of money and deteriorating the pavement.

This study aims at studying the effect of axle load increase, and the variation in the AC pavement modulus, on the overall pavement life. It also aims at estimating the over weight truck axle limits that could be penalized or unloaded.

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**Table 1. Fatigue model coefficients based on different agencies.**

<table>
<thead>
<tr>
<th>No. Procedure</th>
<th>(f_1)</th>
<th>(f_2)</th>
<th>(f_3)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Asphalt Institute</td>
<td>0.0796</td>
<td>3.291</td>
<td>0.854</td>
<td>[4]</td>
</tr>
<tr>
<td>2. Shell Research</td>
<td>0.0685</td>
<td>5.671</td>
<td>2.363</td>
<td>[5]</td>
</tr>
<tr>
<td>4. Belgian Road Research Center (BRRC)</td>
<td>4.92E-14</td>
<td>4.76</td>
<td>0</td>
<td>[1]</td>
</tr>
<tr>
<td>5. Transport &amp; Road Research Laboratory</td>
<td>1.66E-10</td>
<td>4.32</td>
<td>0</td>
<td>[1]</td>
</tr>
<tr>
<td>6. Federal Highway Administration</td>
<td>7.56E-12</td>
<td>4.68</td>
<td>0</td>
<td>[7]</td>
</tr>
<tr>
<td>7. ILLINOIS Department of Transportation</td>
<td>5.00E-06</td>
<td>3.00</td>
<td>0</td>
<td>[8]</td>
</tr>
<tr>
<td>8. Austin Research Engineers (ARE)</td>
<td>9.73E-15</td>
<td>5.16</td>
<td>0</td>
<td>[9]</td>
</tr>
</tbody>
</table>

**Table 2. Rutting model coefficients from different agencies.**

<table>
<thead>
<tr>
<th>No. Procedure</th>
<th>(f_4)</th>
<th>(f_5)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. Belgian Road Research Center (BRRC)</td>
<td>3.05E-09</td>
<td>4.350</td>
<td>[1]</td>
</tr>
<tr>
<td>5. Transport &amp; Road Research Laboratory</td>
<td>1.130E-06</td>
<td>3.570</td>
<td>[1]</td>
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<tr>
<td>6. CHEVRON</td>
<td>1.337E-09</td>
<td>4.484</td>
<td>[10]</td>
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</table>
3. RESEARCH APPROACH

The KENLAYER computer program\textsuperscript{[1]} was used to calculate the tensile strain at the bottom of the asphalt layer and the compressive strain at the top of the subgrade soil. These computed strains are incorporated in the fatigue cracking and rutting models to estimate the pavement life for different axle weights. Different axle loads are considered in this research; the standard 18 kips (8.2 tons) axle load, the previous maximum allowed axle load in Egypt, 10 tons, the new proposed axle load, 13 tons, and additional smaller and larger axle loads (6, 16, 20, 24, 26 & 30 tons). The assumed axles are the most common, more critical, ones having two sets of dual tires with 120 psi (827 kPa) tire pressure and 12 inches (30 cm) dual spacing.

3.1 Layers’ Properties

The elastic modulus of the asphalt concrete (AC) layer is highly affected by pavement temperature, where, the modulus decreases as the temperature increases. Salem\textsuperscript{[13]} and Salem et al.\textsuperscript{[14]} studied the effect of pavement temperature on the AC modulus. He reported that the AC modulus during summer drops to about 20% of its winter value due to the increase in pavement temperature. Therefore, different AC layers’ moduli are considered in this study to represent different climatic conditions from the strongest (greatest) AC modulus during winter to the weakest (smallest) modulus during summer. Their values ranged from 600, 400, 240 & 160 ksi (4140, 2760, 1650 & 1100 MPa). Two different subgrade moduli; 7.5 and 15 ksi (52 & 103 MPa), are considered corresponding to subgrade CBR values of 5 and 10 respectively. The modulus of the aggregate base layer is assumed 50 ksi (345 MPa). The layers’ thicknesses are the typical cross sections commonly used in Egypt which are 10 cm AC layer and 40 cm of the base layer.

3.2 Pavement Life Prediction

The performance models considered in this study are those included in the Asphalt Institute\textsuperscript{[4]} design manual. For fatigue cracking, the manual suggested the following performance coefficients for standard AC mixes with an asphalt volume of 11% and air void volume of 5%:

\[ N_{f1} = 0.414 \varepsilon_i^{-3.291} E^{-0.854} \]  \hspace{1cm} (3)

where the units are in SI units. The rutting model incorporated in the Asphalt Institute design manual is given by the following equation:

\[ N_{r2} = 1.365 \times 10^{-9} \varepsilon_c^{-4.477} \]  \hspace{1cm} (4)

The pavement life or the number of load repetitions to the pavement failure is considered the lower of the number of repetitions to failure obtained from either the fatigue or rutting models.

3.3 Damage Prediction

The prediction of pavement life is based on the cumulative damage concept in which a damage factor is defined as the damage per pass caused to a specific pavement system by the load in question. The damage \((D_i)\) caused by each application of a single axle load at any season can be given by:

\[ D_i = \frac{1}{N_i} \]  \hspace{1cm} (5)

where \(N_i\) is the minimum number of load repetitions required to cause either fatigue or rutting failure, as given by Equations 3 and 4. The total number of load repetitions \((N_f)\) that are allowed over the pavement lifetime can be determined when total cumulative damage \((D_f)\) reaches one. Therefore, Equations 3 and 4 can then be solved for the total allowable number of load applications required to cause either fatigue or rutting failures over the pavement lifetime.

4. ANALYSIS OF RESULTS

Multilayer elastic analysis is performed using the KENLAYER software. The different variables discussed in the previous section are considered. The resulting pavement strains, damage and pavement lives (number of load repetitions to failure) are presented in Figures 1 through 4 for both fatigue (the upper graph, A) and rutting (the bottom graph, B) models. The following sections discuss the outcomes of these figures.

4.1 Effect of Axle Load Increase on Pavement Strains and Damage Ratios

Figure 1 presents the relationship between tensile strain at the bottom of the AC layer and the compressive strain at the top of subgrade soil versus axle load for different AC moduli. The figure shows that the tensile strain increase with higher rate (power function) with increasing the axle load. On the other hand, the compressive strain increases in a linear function with increasing the axle load. It also shows that the rate of increase (slope of the line) is greater with pavement having lower smaller AC modulus.

The estimated fatigue and rutting damage ratios versus axle load are presented in Figure 2 for different AC moduli. The figure shows that the fatigue damage increases in a linear function with increasing the axle load for greater AC moduli, while increases with a higher rate (power function) for lower AC moduli. This would be reasonable since the pavement behaves as an elastic material with greater AC moduli (lower pavement temperature), while behaves as a plastic material with smaller AC moduli (higher pavement temperature). The figure shows also that the fatigue damage generally increases in an increasing rate (diverging) with increasing the axle load, while the rutting damage increases with a decreasing rate (converging).
4.2 Effect of Axle Load Increase on Pavement Fatigue and Rutting Lives

Figure 3 presents the fatigue and rutting lives versus axle load for different AC moduli. The figure shows that both fatigue and rutting lives decrease dramatically with increasing the axle load especially after the axle load exceeds 13 tons. The figure shows also that the variation in the AC moduli is more significant with fatigue life than rutting especially with greater axle loads.

As previously explained, the design pavement life is the minimum number of load repetitions required to cause either fatigue or rutting failure, as given by Equations 3 and 4. Therefore, the optimum axle load that causes both fatigue and rutting failures, at the same time, can be achieved when the difference between rutting and fatigue lives is zero. Figure 4 presents the difference between rutting and fatigue lives. The figure shows that the optimum axle load causing both fatigue and rutting failures, at the same time, ranges from 11 to 14 tons for AC moduli ranging from 1100 to 4140 MPa (summer & winter) respectively. Therefore, the maximum allowable axle load should not exceed 11 tons during the summer season and 14 tons during winter.

Figure 4 indicates also that when the axle loads are smaller than the previously specified load limits (11-14 tones), the difference between rutting and fatigue lives is positive and the pavement failure is mainly affected by fatigue (rutting life is greater than fatigue life). On the other hand, when the axle loads are greater than the previously specified load limits (11-14 tones), the difference between rutting and fatigue lives is negative and the pavement failure is mainly affected by rutting (rutting life is less than fatigue life).
4.3 Effect of Axle Load Increase on the Pavement Design Life

The pavement design life is the minimum number of load repetitions required to cause either fatigue or rutting failure, as given by Equations 3 and 4. In addition, the pavement design life is governed by fatigue failure with smaller axle loads and by rutting failure with greater axle loads. Therefore, the minimum pavement life (based on rutting or fatigue models) is chosen for different axle loads ranging from 10 to 20 tones, and all the estimated lives are then divided by the pavement life corresponding to the 10 tones axle load and the result is presented in Figure 5. The figure shows the decrease in the pavement design life with increasing the axle loads. It can be easily noted from the figure that when the axle load increases from 10 to 13 tons the pavement design life decreases to about 40% of its value with pavements having lower AC modulus (summer), and to about 65% of its value with pavements having stronger AC modulus (winter). On the other hand, when the axle load increases from 10 to 16 tons, the pavement design life decreases to only about 16% of its value with lower AC modulus (summer), and to about 30% of its value with stronger AC modulus (winter). This observation should be taken seriously when dealing with overweight trucks.

The highway authorities should take the previous observations into account. Therefore, by allowing the axle loads to increase from 10 to 13 tons, the pavements will only last approximately one half of its design life compared with the 10 tons axle. Further increase in the axle loads should not be allowed, even with penalties, because it will cause a quick deterioration to the pavement (about one third of its life when the axle load increases from 10 to 16 tons).
Figure 3. Fatigue and rutting lives versus axle load for different AC moduli.

Figure 4. The difference between rutting and fatigue lives for different AC moduli.
5. CONCLUSIONS

Based on this study the following can be concluded:
1. The optimum axle load causing both fatigue and rutting failures at the same time, ranges from 11 to 14 tons for AC moduli ranging from 1100 to 4140 MPa (summer & winter), respectively.
2. The maximum allowable axle load should not exceed 11 tons during summer season and should not exceed 14 tons during winter.
3. The pavement design life is generally governed by fatigue failure with smaller axle loads (less than 11 tons) and by rutting failure with greater axle loads.
4. By allowing the axle loads to be increased from 10 to 13 tones, the pavements will last to only one half of its design life compared to the 10 tons axle.
5. Single axle loads greater than 14 tons should not be allowed even with penalties because it will cause a quick deterioration to the pavement, especially during summer.

References
